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EUV spectroscopy on the SSPX spheromak

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Abstract. EUV plasma spectroscopy is one the diagnostics implemented at the Sustained Spheromak Physics Experiment (SSPX) at the Lawrence Livermore National Laboratory. A grating spectrometer covering the spectral region of 25 - 450 Å with a resolution of 0.4 Å was used as an impurity diagnostic to monitor the plasmas and to carry out atomic physics research. Several low-Z impurities have been found in the spheromak, notably B, C, N, and O. Of the heavier elements, Ti, Cu, and W were found in the plasmas. As a relatively dense and low-temperature laboratory plasma device, SSPX served as an excellent radiation source for investigation of atomic spectra in a regime not readily attained in other devices. We have injected atomic titanium and tungsten hexacarbonyl into the spheromak under different operating conditions. We also report on electron temperature and electron density measurements based on the Kα lines from B IV at 60 Å.

1. Introduction

Impurity ions serve a beneficial role in the plasmas generated for magnetic fusion research, because as trace elements they provide critical diagnostic information on the state of the plasma [1]. In large quantities, however, they may constitute a problem for magnetic confinement fusion. The presence of contaminants in a fusion device effectively cools and dilutes the plasma [2, 3], making it more difficult to achieve ignition. Impurities in large quantities, where their radiation significantly affects the power balance, may also affect the magnetic stability of the plasma [2, 3] and hence disturb the operation of the device. Being able to assess impurity concentrations via spectroscopic means is thus essential.

The atomic physics plays a crucial role for developing impurity radiation as a diagnostic. By spectroscopically studying the line radiation emitted from a plasma, information about parameters such as electron temperature, ion temperature, electron density and impurity species can be gained, to name a few. For instance, certain atomic transitions are density and temperature sensitive and their line intensities can provide information of these parameters. The well known K-shell lines from He-like atoms are one such example, constituting a useful diagnostic for high-temperature plasmas [4]. The three main features of the Kα signature are the resonance line w $1s^2\ {}^1S_0 - 1s2p\ {}^1P_1$, the intercombination line y $1s^2\ {}^1S_0 - 1s2p\ {}^3P_1$, and the forbidden line z $1s^2\ {}^1S_0 - 1s2s\ {}^3S_1$ [5, 6]. The relative intensities in the signature can provide data about plasma densities and electron temperatures, making He-like ions very attractive diagnostics since they have the widest abundance range in high-temperature plasmas of any isoelectronic species [7].

In addition, impurities can also benefit atomic physics research, given that the optically thin magnetic confinement plasmas act as good sources of radiation [8]. These sources can provide production of highly charged ions difficult to attain otherwise. Magnetic confinement plasmas in near coronal equilibrium moreover permit higher-order, i.e. dipole forbidden, radiative transitions to occur and hence can find use as experiments of astrophysical importance [9]. Fusion experiments can therefore offer valuable atomic data for charge balance modeling and atomic structure research.

In the EUV spectral range many strong atomic transitions take place, making this region a rich area for spectroscopy. The L-shell transitions in low-Z elements such as C, N, and O fall within the EUV, as do many $n' = 3 \rightarrow n = 3$ for mid-Z ions such as Ti and Cu. In moderately high-temperature plasmas, such as spheromaks, conditions are favorable for the production of charge states with ample EUV transitions.

The Sustained Spheromak Physics Experiment at the Lawrence Livermore National Laboratory (LLNL) was an effort in the field of innovative confinement concepts (ICC), with the main objective to explore energy confinement and current drive in spheromaks [10]. Spheromaks confine plasmas using self-organized magnetic fields [10], thus making external coils superfluous, an important advantage over the tokamak design. The toroidally shaped SSPX plasmas had a major radius of $R = 0.31$ m and a minor radius of $a = 0.23$ m, confined within a cylindrical flux conserver of diameter 1.0 m and height 0.5 m. The flux conserver was made of copper with tungsten-coated surfaces to reduce sputtering of wall material [11]. From the coaxial gun and gas injector region atop the flux conserver the plasmas were created and pushed downward into the flux conserver forming the spheromaks [11]. Plasma currents achieved magnitudes of up to 1 MA [12]. Typical SSPX plasmas lasted around 4 ms, with plasma densities of a few times 10^{14} cm^{-3} [13]. Peak electron temperatures at the magnetic axis ranged up to, and exceeded, 500 eV, a record temperature for spheromaks [14, 12].

Our diagnostic consisted of an EUV grazing incidence spectrometer, known as the Silver Flat Field Spectrometer (SFFS). Similar to other spectroscopic instrumentation used on magnetic fusion devices [15], the instrument was developed at the Livermore EBIT facility. Its design is similar to the design described in [16]. The flat-field spectrometer employes a spherical 1200 lines/mm grating [17], giving a resolution of 0.4 Å over the spectral range 25 - 450 Å. The image detection was done using a back-illuminated Photometrics CCD camera, allowing a bandwidth of about 200 Å per image.

2. Measurements

The Silver Spectrometer was added to the instrumentation at the SSPX facility in 2006 to replace the Survey, Poor Resolution, Extended Domain (SPRED) spectrometer [18, 19]. With the primary purpose to study impurity ions, the SFFS was a standard part of the diagnostics suite during the last year of SSPX operations. With a field of view through the magnetic axis at the midplane of the plasma torus, the SFFS studied spheromaks under various conditions. Due to the short plasma discharges the CCD camera had to record time-integrated images. The resulting spectra thus show time-integrated lines over the spatially integrated plasma chord. For most measurements a 100 μm slit was used to image the plasmas onto the grating.

To get acquainted with the spheromak spectra in the initial phase of SFFS operations, we injected He gas into the plasmas to provide wavelength calibration. With the Rydberg series in He II and an aluminum cutoff filter in front of the grating blocking radiation below 170 Å we were able to establish the instrumental coverage.

2.1. Impurity diagnostics

Two sets of low-temperature experiments monitored by the SFFS were internal magnetic measurements to study spheromak formation and evolution. The studies were done using boron nitride covered probes [20, 21, 22] inserted into the spheromak. During the discharges the coating evaporated, which added B and N to the plasmas, thus cooling the electrons to temperatures of some tens of eV. Spectra from these shots are rich of lines, and numerous transitions from B, C, N and O have been identified, see Figures 1 and 2. The oxygen ions originate mainly from water vapor inside the vacuum vessel, and are typically the most abundant contaminants in SSPX plasmas.

Another experimental campaign was undertaken with the aim to extend the flux conserver height by inserting uncoated copper rods between the upper and lower sections [14]. The SFFS recorded many interesting spectra with quite different features from earlier studies. The discharges effectively sputtered material off the exposed copper surfaces, seeding the plasmas with large amounts of Cu in various charge states.

Other impurity ions found in the spheromak were Ti and W, which we verified by injecting Ti and $W(CO)_6$ into SSPX, as discussed below.

2.2. Injection of metals

Ti is an abundant impurity in the spheromak, occurring in weakly ionized states (typically Ti V - Ti VIII). With the purpose to clean the spheromak and reduce hydrogen recycling Ti is introduced on the plasma facing surfaces of the flux conserver by a vapor deposition method known as titanium gettering. We utilized this as an injection method to enhance the Ti impurity concentration and studied how the spectra changed with time, i.e. subsequent shots after Ti gettering. As expected, there existed more Ti in the plasmas immediately after gettering, and the Ti was found to successively wear off the flux conserver during subsequent discharges and to be pumped away from the vessel. By tracking various candidate titanium lines over many such discharges we could unequivocally establish them as emanating from titanium ions.

Another injection experiment we performed was to introduce the gaseous compound tungsten hexacarbonyl $W(CO)_6$ into the spheromak to study relatively weakly ionized W. By introducing tungsten hexacarbonyl into the plasmas various unidentified lines observed in earlier SSPX discharges could be attributed to transitions in tungsten. As mentioned before, tungsten was used to coat the flux conserver. We note that the SSPX spheromak was an ideal test bed for investigating W spectra under plasma conditions similar those of future ITER divertor plasmas, because ITER divertor plasma parameters (electron temperatures below 100 eV and densities of $10^{14} - 10^{15}$ cm^{-3} [23]) are essentially the same as those found in SSPX plasmas. The spectral lines produced in SSPX should prove useful as ITER divertor diagnostics.

2.3. Temperature and density diagnostic

The shortest wavelength lines so far analyzed among the SSPX data are from He-like B IV during the magnetic probe measurements, see Figure 2. The Kα line pair w at 60.3144 Å and y at 61.088 Å [24] were used to make estimates of electron temperatures and electron densities of the plasmas during one set of the magnetic probe experiments. Flexible Atomic Code [25] calculations were made as a function of electron temperature and density, as shown in Figure 3. Based on the mean value of around 0.2 of the measured y/w ratio, the atomic physics restricts the electron density to about 1 $\times 10^{12}$ - 2 $\times 10^{14}$ cm^{-3}, and a temperature interval of about 20 - 100 eV. The boron emission therefore comes from either low-density, high-temperature regions of the spheromak or high-density, low-temperature regions. The line-averaged density through the magnetic axis of the spheromak (for shot 16644 shown in Figure 2) was determined using a CO_2 laser interferometer system [13, 26] to be between 1 - 5 $\times 10^{14}$ cm^{-3} at different times during the main part of the discharge. These densities are at the high end of the values given by the calculations. This suggests that the boron emission comes from the cooler edge of the plasma. We therefore hypothesize that the boron, originating from the magnetic probe at the edge of the plasma, likely has a hollow density profile due to slow diffusion. Considering that B III ionizes at 38 eV and the B IV Kα lines require energies in excess of 200 eV, along with the expected lower electron temperatures at the outer flux surfaces, we infer that only few high-energy electrons in the Maxwell-Boltzmann distribution are responsible for the excitation, which explains why these lines are very weak.

3. Summary

Our efforts at the SSPX facility have shown the value of spheromak spectroscopy for the study of atomic spectra believed to be of importance for future large tokamak experiments. We have performed temperature and density measurements employing the relative intensities of He-like spectral lines, and made an inventory of the impurity ions in the SSPX spheromak.

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References

[1] Stratton B C, Bitter M, Hill K W, Hillis D L and Hogan J T 2008 *Fusion Sci. Technol.* **53** 431
[2] Wesson J 1997 *Tokamaks* (Oxford University Press)
[3] Wenzel K W 1989 *Measurements of Injected Impurity Transport in TEXT Using Multiply Filtered Soft X-Ray Detectors* Ph.D. thesis Massachusetts Institute of Technology, Plasma Fusion Center
[4] Bitter M, von Goeler S, Suthoff N, Hill K, Brau K, Eames D, Goldman M, Silver E and Stodiek W 1981 *International Conference on X-Ray Processes and Inner-Shell Ionization* ed Fabian D J, Kleinpoppen H and Watson L M p 861
[5] Gabriel A H 1972 *Mon. Not. R. Astr. Soc.* **160** 99
[6] Gabriel A H and Jordan C 1969 *Mon. Not. R. Astr. Soc.* **145** 241
[7] Pradhan A K and Shull J M 1981 *Astrophys. J.* **249** 821
[8] Beiersdorfer P, von Goeler S, Bitter M and Hill K W 1989 *Nucl. Instrum. Meth. Phys. B.* **43** 347
[9] Beiersdorfer P 2003 *Ann. Rev. Astron. Astrophys.* **41** 343
[10] Wood R D, Hill D N, Hooper E B, McLean H S, Ryutov D and Woodruff S 2005 *J. Nucl. Mater.* 548
[11] Wood R D, Hill D N, Hooper E B, Woodruff S, McLean H S and Stallard B W 2005 *Nucl. Fusion* **45** 1582
[12] Hudson B, McLean H S, Wood R D, Hooper E B, Hill D N, Jayakumar J, Moller J, Romero-Talamas C, Casper T A, Johnson III J A, LoDestro L L, Mezonlin E and Pearlstein L D 2008 *Phys. Plasmas* In press
[13] Wang Z, Wurden G A, Barnes C W, Buchenauer C J, McLean H S, Hill D N, Hooper E B, Wood R D and Woodruff S 2001 *Rev. Sci. Instrum.* **72** 1059
[14] Wood R D, Hill D N, McLean H S, Hooper E B, Hudson B F and Moller J M Submitted to Phys. Rev. Let.
[15] Graf A T, Brockington S, Horton R, Howard S, Hwang D, Beiersdorfer P, Clementson J, Hill D, May M, McLean H, Wood R, Bitter M, Rice J, Terry J and Rowan W L 2008 *Can. J. Phys.* **86**
[16] Beiersdorfer P, Crespo López-Urrutia J R, Springer P, Utter S B and Wong K L 1999 *Rev. Sci. Instrum.* **70** 276
[17] Kita T, Harada T, Nakano N and Kuroda H 1983 *Appl. Optic.* **22** 512
[18] Fonck R J, Ramsey A T and Yelle R V 1982 *Appl. Optic.* **21** 2115
[19] Stratton B C, Fonck R J, Ida K, Jaehnig K P and Ramsey A T 1986 *Rev. Sci. Instrum.* **57** 2043
[20] Romero-Talamás C A, Bellan P M and Hsu S C 2004 *Rev. Sci. Instrum.* **75** 2664
[21] Romero-Talamás C A, Hooper E B, Hill D N, Cohen B I, McLean H S, Wood R D and Moller J M 2007 *J. Fusion Energ.* **26** 169
[22] Romero-Talamás C A, McLean H S, Hooper E B, Wood R D, LoDestro L L and Moller J M 2007 *J. Fusion Energ.* DOI 10.1007/s10894-007-9110-5
[23] Skinner C H 2008 *Can. J. Phys.* **86** 285
[24] Kelly R L 1987 *J. Phys. Chem. Ref. Data* **16**
[25] Gu M F 2008 *Can. J. Phys.* In press
[26] McLean H S *et al.* 2001 *Rev. Sci. Instrum.* **72** 556

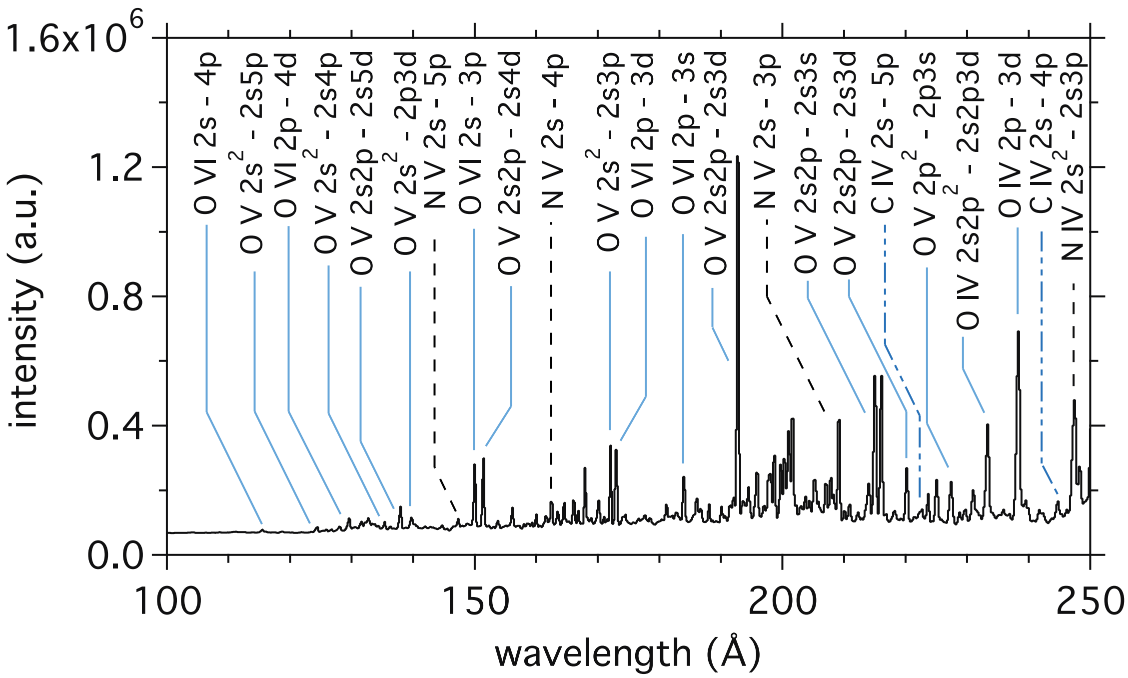

Figure 1. SSPX shot 18415. Spectral lines from O [solid cyan blue], N [dashed black], and C [dot-dashed dark blue]. Most of the remaining lines are from Ti, Cu, and W as described in the text.

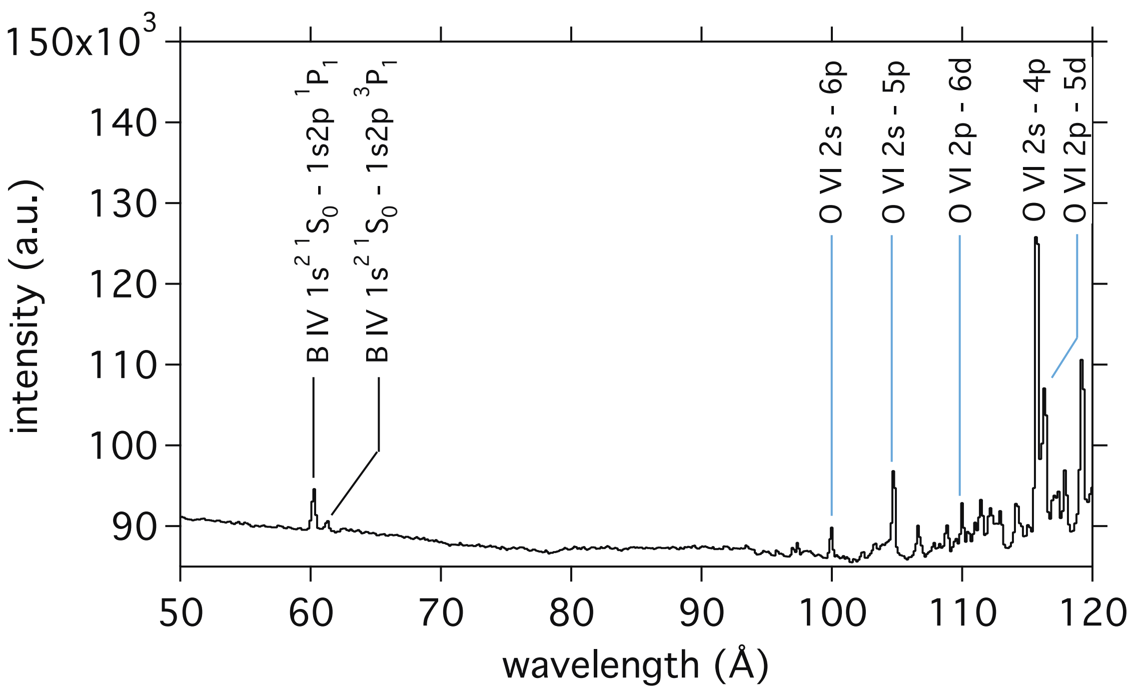

Figure 2. SSPX shot 16644. He-like B IV Kα lines [black] and Li-like O VI [cyan blue].

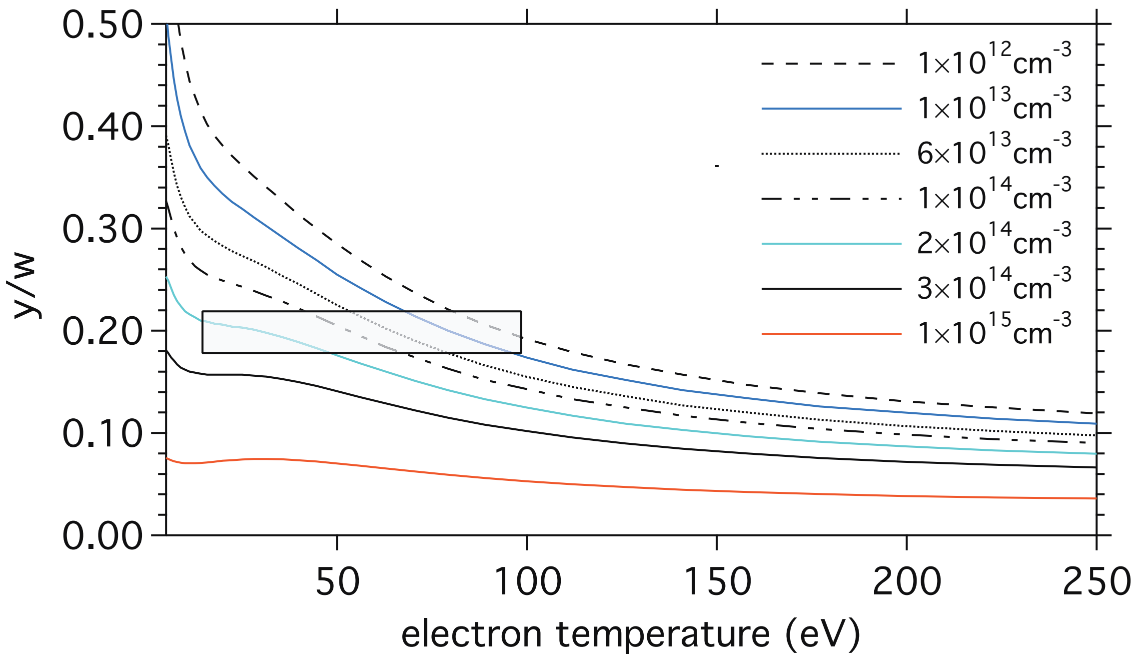

Figure 3. Flexible Atomic Code calculations of the ratio y/w as a function of electron temperature and density. Gray box shows interval of parameter space for the SSPX B IV emission.

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